GOATS' 2000
Multi-Static Active Acoustics in Shallow Water

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LONG-TERM GOAL

Develop environmentally adaptive bi- and multi-static sonar concepts for autonomous underwater vehicle networks for detection and classification of proud and buried targets in very shallow water.

OBJECTIVES

The objective of the ocean acoustics components of the GOATS project is to develop a fundamental understanding of the 3D mid-frequency (1-20 kHz) acoustic environment associated with the mine countermeasures (MCM) problem in shallow water (SW) and very shallow water (VSW) and to develop efficient physics based propagation and scattering models incorporating aspect-dependent targets and seabed features, and the waveguide multipath effects. The goal is a consistent physics-based modeling framework for high-fidelity simulation of bi-and multistatic sonar configurations for VSW MCM which may form the basis for new acoustic classification techniques based on spatial and temporal target resonance characteristics. Specific scientific objectives include the investigation of mechanisms responsible for sub-critical penetration into sediments in the mid-frequency regime (1-20 kHz), the effects of sediment porosity, and the coupling between the structural acoustics of targets and the environmental acoustics of the littoral waveguides.

APPROACH

The development of GOATS (Generic Ocean Array Technology Sonar) is a highly interdisciplinary effort, involving experiments, and theory and model development in advanced acoustics, signal processing, and robotics. The center piece of the research effort is the GOATS'2000 Joint Research Program (JRP) conducted by SACLANTCEN and MIT with ONR support, which was scheduled to finish in Aug. 2001, but which has been extended with 5 years, formally incorporated in the SACLANTCEN Program of Work. Building on the experience of the highly succesful GOATS'98 pilot experiment [2] and the GOATS'2000 [9] experiment, the JRP continues with a series of experiments, with the two major ones being planned for 2002 and 2004, and modeling and simulation work to explore the potential of autonomous underwater vehicle networks as platforms for new sonar concepts exploring the full 3-D acoustic environment of VSW. The modeling effort is centered around the OASES environmental acoustic modeling framework developed at MIT [1,4]. OASES is a widely distributed suite of models covering a variety of ocean waveguide and source/receiver representations.

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Thus, the most recent developments are computational modules for full wave theory modeling of mono-and bistatic reverberation in shallow water waveguides. In collaboration with SACLANTCEN the waveguide reverberation code OASSP has been modify to consistently model the mono- and bistatic reverberation from interface roughness and seabed volume inhomogeneities in azimuthally symmetric sonar scenarios [6]. Another module, OASES-3D provides wave-theory modeling of the full 3-D acoustic environment associated with mono- and bi-static configurations in VSW with aspect-dependent targets and reverberation features [3,4]. OASES-3D incorporates environmental acoustic features specifically associated with bi-static sonar concepts in shallow water, including aspect-dependent target models, seabed porosity, and scattering from anisotropic seabed roughness such as sand ripples. The validation of these models is one of the major objectives of the GOATS JRP with SACLANTCEN.

Fig. 1. (a)GOATS'2000 range in Biodola Bay, Elba, with TOPAS parametric projector and bottom mounted targets and natural seabed ripple fields. (b) Deployment of Odyssey bistatic receiver AUV from RV Alliance, Sep. 25, 2000.

WORK COMPLETED

The most significant component of the FY01 has been associated with the execution of the GOATS'2000 experiment in Golfo di Procchio, Elba Island, carried out as a Joiunt Research Project (JRP) with SACLANT Undersea Research Centre in the period Sep. 18 – Oc. 14, 2000. The experiment collected a variety of ocenographic and navy resources for performing rapid environmental assesment (REA) and mine countermeasures (MCM) in shallow (SW) and very shallow water (VSW). A fleet of 4 AUV's were operated from R/V Alliance. One MIT Odyssey II was equipped with an 8-element acoustic array in a 'swordfish' configuration serving as bistatic receiver for measuring the 3-D scattering from natural ripple fields and aspect dependent targets deployed on and within the seabed. The seabed was insonified by a TOPAS parametric source on a stationary tower. In addition, a second Odyssey II AUV was equipped with an Edgetech subbottom profiler which to be used as a moving bistatic source and for REA missions. This AUV was succesfully configured and prepared for these missions, but the dual vehicle missions were not succesfully completed due to mechanical and electrical failures in this vehicle.

A third AUV, an FAU Ocean Explorer was equipped with a sidescan system for seabed mapping and multiaspect target classification. This vehicle was succesfully operated by FAU and SACLANTCEN.

Finally, a Taipan AUV is operated by a group from LIRMM in France, collecting CTD data in Procchio Bay. This data is assimilated into a nested ocean forecasting framework together with CTD, XCTD, and XBT data collected by R/V Alliance during nightime operations.

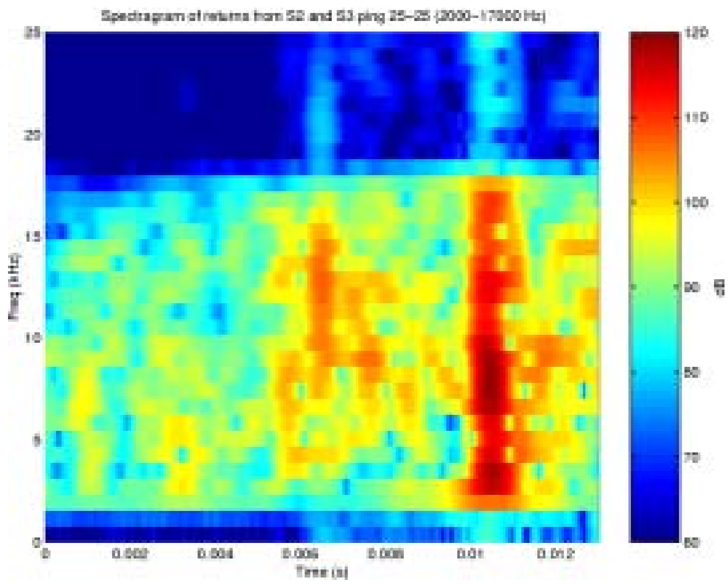

Figure 1 The spectrogram of the beamformed time series for file 25 centered on S2. Clearly visible is the time frequency response of the flush buried sphere S2, between times of 6 and 8 ms. Below 8 kHz, S2 has one weak return at 6 ms, while in the 8-15 kHz range there are two distinct returns, the second of which is considered to be a membrane wave multipath of the sphere. The return from the proud sphere S3 is clearly visible at 10.5 ms.

On the acoustic modeling and analysis side, the bulk of the effort in FY01 has focused on understanding the physics associated with scattering from buried targets, in particular for subcritical insonification. The data set collected during the GOATS'98 experiment is extremely rich and close to ideal for such analysis, with its wide suite of fixed and mobile, mono- and bistatic arrays, and the extensive supporting environmental characterization (Schmidt etal. 1998, Maguer et al. 2000). This analysis has led to new understanding of the fundamental differences between the scacttering processes associated with sub- and supercritical insonification, and the need for full wave theory modeling for accurately modeling the scattering associated with the exciutation of structural waves in shallow-buried targets, as discussed in the following and in more detail in Ref. [5] .

RESULTS

AUV Data processing

The analysis of the particular role of elastic wave scattering in the case of subcritical scattering from buried targets was triggered by some unexpected results produced by the synthetic aperture processing of the bistatic data collected by the AUV. Thus, for example, Fig. 1 shows the spectrogram of the timeseries obtained by beamforming over a 6.2 m bistatic synthetic aperture along one of the survey tracks, focused on the nominal seabed position of the flush-buried sphere S2 [2]. This result clearly demonstrates that the maximum scattering from the target occurs at 10-12 kHz, in strong contrast to the much lower optimal frequency expected from traditional point-scatter modelling from simpler targets [7]. An initial arrival with a peak frequency at 5 kHz is evident as well, although at much weaker amplitude.

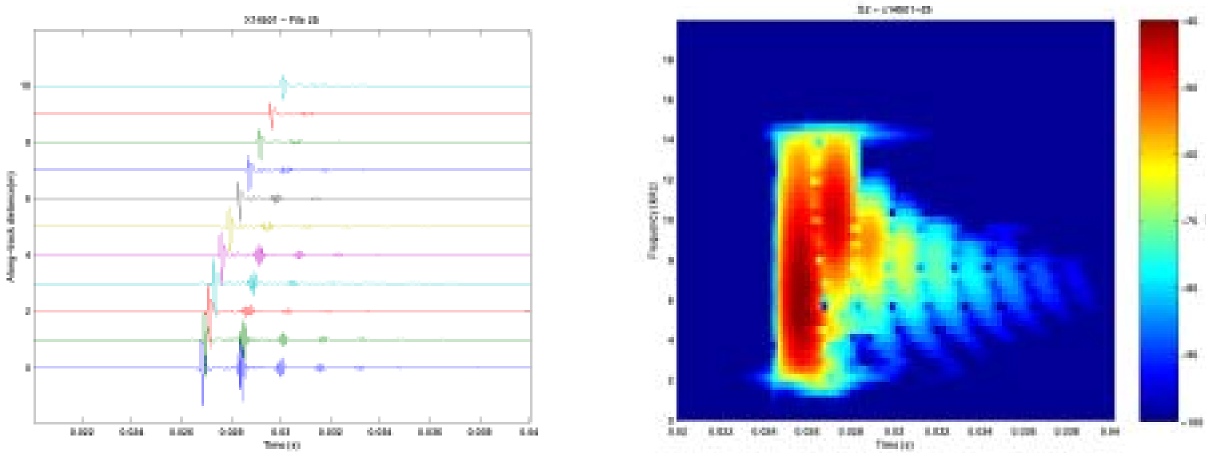

Figure 2 OASES-3D synthetics of scattering from the flush-buried target S2 along a 10 m long synthetic aperture corresponding to the AUV track used for the SAS processing in Fig. 5(a) Synthetic time series at receivers spaced 1 m apart, with 0 m corresponding to a position on the source-target axis. (b) Spectrogram of timeseries at receiver position 0 m.

The parallel SAS imaging work of Edwards *et a*l. [16], [17] has shown that in addition, the imaging shows the target to be displaced by approximately 1 m further away than its actual position, independently determined *in sit*u. These experimental findings lead to the hypothesis that the SAS imaging over the bistatic aperture was dominated by an elastic scattering component, rather than the expected 'specular' scattering of the evanescent, lateral wave. As shown in the following, the OASES-3D model supports this hypothesis, even though some discrepancies still exist and are the target of continued modelling and analysis effort.

OASES-3D Modeling

OASES-3D has been used to simulate the scattering from the target during mission x9814501 used in the analysis described above. The TOPAS source was positioned on a 10 m tall tower, 29.5 m from the target S2, which was insonified at 18.7 deg grazing angle, well below the critical angle independently estimated at 24 deg [7]. Micronavigation relative to the strong target S3 estimated the AUV track to be approximately perpendicular to the source-target axis, passing between the two at a distance of 3.8 m from S2 at the point of closest approach. The synthetic timeseries at 1 m spacing over a 10 m synthetic aperture are shown in Fig. 2(a). Figure 2(b) shows the spectrogram of the signal at the point of closest approach. The initial, strong arrival is the specular reflection of the incident lateral wave, appearing as a low-pass filtered replica of the 8 kHz Ricker wavelet emitted by the TOPAS, as expected. According to the spectrogram this arrival has a maximum at approximately 5 kHz. During the first approximately 1 ms following the specular scattering, a couple of arrivals are observed corresponding to the two first multiples of the longitudinal S0 Lamb wave excited in the shell [10], following which a strong return appears on receivers close to the source-target axis in particular. This is the first ‘flexural’ shell wave, and as evidenced by the spectrogram, it has maximum frequency content at 10-12 kHz, with insignificant energy below 8 kHz. This frequency distribution contrasts to the one observed in the super-critical data, extensively investigated by Tesei *et a*l. [10] which showed a maximum in the A0 response at the 8 kHz coincidence frequency, with the subsonic A0- and the supersonic A0+ modes dominating below and above the coincidence frequency, respectively.

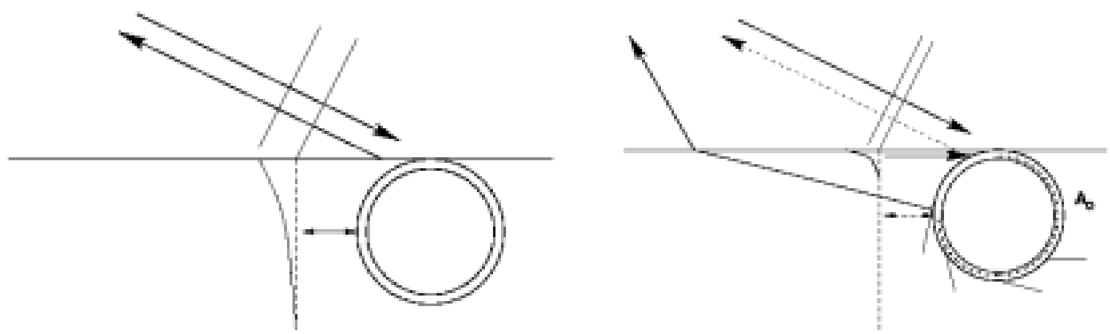

Figure 3 Schematic representation of subcritical scattering from a flush-buried spherical shell. (a) At low frequencies the scattering is dominated by the specular scattering of the evanescent, lateral wave, with the back-scattering being excited by wave tunnelling. (b) At high frequencies the 'specular' component becomes insignificant, and elastic waves dominate.

These results suggest that the physics of subcritical scattering from a flush-buried spherical shell is as sketched in Fig. 3. At low frequencies, Fig. 3(a), the back-scattering is dominated by the specular scattering of the evanescent, lateral wave. Thus, for a subcritical receiver the back-scattering is being excited by wave tunnelling, with an exponential decay with frequency as a result. In contrast, as illustrated in Fig. 3(b), at high frequencies the ‘specular’ component becomes insignificant because of the shallow penetration depth of the lateral wave. However, for shallow burial depth the target curvature near the seabed allows this evanescent ‘tail’ to couple efficiently into the ‘flexural’ A0 Lamb waves, of which the supersonic A0+ component will radiate directly into the sediment. This radiated field will transmit into the water column at super-critical angles, even for receivers which are ‘sub-critical’ in a geometrical sense. Thus, the associated energy will arrive at water column receivers at angles ranging from vertical for a receiver above the target to the critical angle at distant receivers. Consequently, for subcritical insonification the specular arrival will be low-pass filtered relative to the incident field while the flexural Lamb wave becomes high-pass filtered because of the more effective re-radiation into the sediment and back into the water column of the supersonic A0+ above the coincidence frequency. The multiples of the A0+ appear from the spectrogram to have decreasing peak frequency, which is explained by the linear frequency attenuation.

IMPACT/APPLICATION

The long-term impact of this effort is the development of new sonar concepts for VSW MCM, which take optimum advantage of the mobility, autonomy and adaptiveness of the AOSN. For example, bi- and multi-static, low-frequency sonar configurations are being explored for buried mines in VSW, with the traditional high-resolution acoustic imaging being replaced by a 3-D acoustic field characterization as a combined detection and classification paradigm, exploring spatial and temporal characteristics which uniquely define the target and the reverberation environment.

TRANSITIONS

The GOATS AUV effort has been and is conducted by the MIT Sea Grant AUV Laboratory, in part funded by this project and the AOSN MURI. A new AUV enterprice, Bluefin Robotics, is a spin-off from the MIT Laboratory, and is currently developing a new Odyssey III Battlefield Preparation AUV for ONR, building in part of experience from the GOATS`98 experiment [2].

The 3-D acoustic models for VSW MCM environments developed under GOATS are being integrated in a multi-AUV simulation capability developed by the MIT Sea Grant AUV Laboratory and Bluefin Robotics under the ONR project (Code 321TS) “Sensor and Operational Tradeoffs for Multiple AUV MCM” (N00014-99-1-0851). Also, the simulation capability is being utilized and augmented under the ONR SBIR (code 321OE) “USBL Positioning of Littoral Swarm Systems” (N00014-97-C-0288) in collaboraion with IS Robotics. The new OASES seabed reverberation modeling capability (LePage and Schmidt 1999) is the core modeling engine used by VASA Associates Inc. in the FY00 ONR SBIR “Model-Based Beam-Time Arrival Matching” (N992-5039).

The OASES code continues to be maintained and expanded. It is continuously being exported or downloaded from the OASES web site (http://acoustics.mit.edu/arctic0/henrik/www/oases.html), and used extensively by the community as a reference model for ocean seismo acoustics in general.

RELATED PROJECTS

This effort is part of the US component of the GOATS`2000 Joint Research Project (JRP) with the SACLANT Undersea Research Centre. The MIT GOATS effort is funded jointly by ONR codes 321OA (Simmen), 321OE (Swean), 321TS (Johnson), and 322OM (Curtin).

The GOATS effort is strongly related to the ONR Autonomous Ocean Sampling Network (AOSN) initiative completed in FY00. Thus the GOATS’98 experimental effort was funded in part by the AOSN MURI, (PI: J. Bellingham). In terms of the fundamental seabed penetration physics there are strong relations to the High-Frequency Bottom Penetration DRI (PI: E. Thorsos). This effort also builds on acoustic modeling efforts initiated under the Sea-Ice Mechanics Initiative (SIMI), and continued under funding from ONR code 321OA (Simmen).

With its heavy focus on Synthetic Aperture Processing approaches and their extension to bi- and multistatic configurations in multipath SW VSW environments, there are strong relations to the ONR SASSAFRASS project (code 321TS and 321OA).

With funding from the Sea Grant College program, a regional New England effort involving MIT, WHOI and URI is developing a new rigid mooring concept with GPS sensor tracking for long-term VSW acoustic experiments, e.g exploring reverberation and ambient noise statistics, and tomographic networks for littoral environments. The first scientific apllication concerns the spectral characteristics of seabed scattering and this work is using the new 3-D scattering models developed under this project extensively.

The OASES modeling framework being maintained and upgraded under this contract is being used intensively as part of the MIT AREA (Adaptive Rapid Environmental Assesment) component of the new ONR "Capturing Uncertainty" DRI (Grant # N0014-01-1-0817), aimed mitigating the effect of sonar performance uncertainty due to environmental uncertainty by adaptively deploying environmental assesment resources.

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